Trabajo Fin de Grado
Grado en Ingeniería de las Tecnologías Industriales

Incorporación de celdas de desalación microbianas a pequeños sistemas de desalación con energías renovables

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Universidad de Sevilla
Sevilla, 2017

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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

Sevilla, 2017

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A aquellos los profesores y compañeros que han hecho posible que llegase este momento.

A Lourdes García Rodríguez por tener tanta dedicación conmigo y mi proyecto, y por tener un entusiasmo contagioso para con el trabajo.

Especialmente a mi madre, por hacer de mi la persona que soy. Por nunca dejar de apoyarme.

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1. Introduction

Main objective of this work is the preliminary assessment of integrating a developing technology within a conventional desalination plant in order to reduce the energy consumption of fresh water production from seawater.

Lately, the search to improve industrial methods has focused fundamentally on the environmental and energy cost aspects of our industries, making us more aware of our impact.

Under these circumstances, the research of new technologies has increased exponentially during the last decade. Thus, appeared some interesting procedures which are expected to be the new energy generator technologies in the close future.

A thermoeconomic analysis of one of those new technologies, applied to water desalination, composes a big part of this document, the Microbial Desalination Cells (MDC). These cells are considered the best suit to support well-established processes as the desalination through reverse osmosis (RO) or electrodialysis (ED) are. Recent studies consider MDCs as a possibility due to its ability to produce energy, which would be used to support itself with no input needed.

Firstly, a brief explanation of the methodology followed is made, which illustrates how was performed the thermoeconomic study for the installation analysed. Moreover, an exposition of a recent lab scaled experiment works as an index to identify every step of the setup.

The thermoeconomic analysis includes an exergetic analysis of the different flows, of which the system is composed. Also, this analysis comprehends an economic study about the components of which the cells are composed. On this matter, this chapter expresses the variety of configurations being investigated nowadays in this sector. Finally, the document concludes with the possible implantation of these cells as part of existing systems and its estimated cost.

2. Methodology

Firstly, the analysis determinates the main fundaments of thermoeconomics. Then, a diagram of the basic function of these cells is used to make an exergetic analysis of the flows. The exergetic analysis gives essential information about the relations between flows. In addition, this information along with the main hypothesis, lead to the actual implementation of the equations composing the thermoeconomic analysis. Finally, an economic study of the equipment and its inclusion in installations powered by renewable energies conclude this project.

3. Future and Present Perspective of Desalination

The rising need of drinking water for human consumption makes possible the appearance of new research about technologies based on electrical and thermal energy. These technologies could change the composition of wastewater and seawater into drinking water. Despite the popularity of some traditional technologies, like the Reverse Osmosis (RO), some drawbacks have not been solved like its high-energy cost and environmental impact.

Looking for a solution to these topics, new treatments are being studied. Those are focused on overcoming desalination drawbacks basically through renewable energies. Different options have been designed, as the use of sunlight, the movement of the waves or microorganism as the main power to proceed with the desalination.

On the one hand, the sun might be used to power desalination processes. In this case, photovoltaic technology showed a better efficiency providing energy.

On the other hand, companies like *Resolute Marine Energy* are investigating efficient wave-driven prototypes of desalination systems. This means it would be powered by the currents, thanks to its designs, where a basic RO plant would be located on-shore, while the actual prototype floats off-shore able to make the most of the movement of seas and oceans.

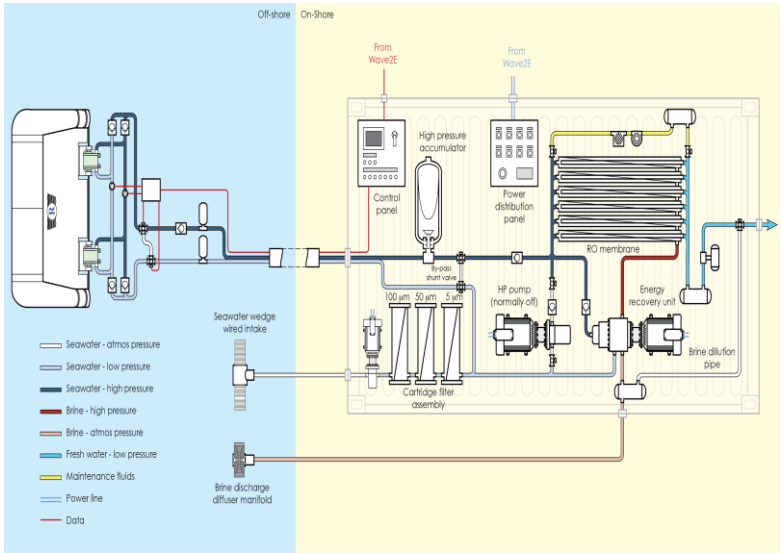


Figure 1 Wave2O Prototype by Resolute Marine Energy

Finally, it has been designed an innovative technology of desalination cells, composed by alive electroactive microorganisms as part of its components. Because of the electricity generated

by the organisms, it would be used to support the cells itself by means of driving a conventional electrodialysis process. An advanced prototype of MDC is being developed within the framework of MIDES project coordinated by the company Aqualia with the relevant participation of the IMDEA Water Institute. Even though this technology is still on preliminary phase, it is considered the possible new implantation as a component of RO plants, in order to reduce its energy cost. Because of the electricity generated by the organisms, it would be used to support the cells itself. The purpose of the MDC would be to reduce the salinity of the water pumped to the RO equipment hence decreasing the overall function cost.

Apart from the research focused on low generation cost for desalination plants, additional equipment was developed for this sector. Sophisticated new generation of biomimetic membranes, which thanks to the microstructures, make possible to allow the selective pass of water molecules.

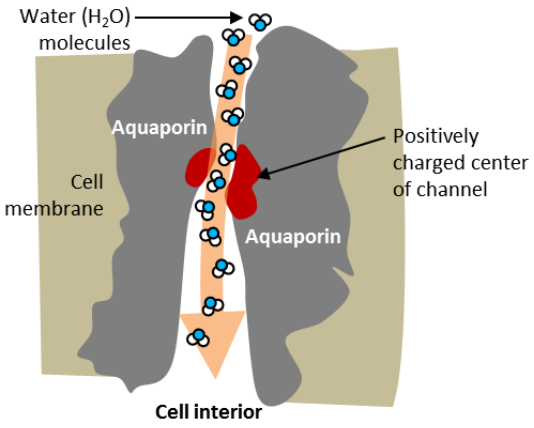


Figure 2 membrane design (Tang et al., 2015)

4. Microbial Desalination Cells

Currently, the most suitable study with opportunities to become a real improvement to water desalination is that focused on developing Microbial Fuel Cells (MFC). Moreover, it looks like a suitable option to decrease the cost and contamination related to the production of desalinated water when a MFC is integrated with other desalination systems. Thanks to experimentations made at lab scale, this kind of methods are stepping forward on the way to becoming the new path for desalination as it is explained in this section, based on Ortiz, Borjas, Rogalla & Esteve-Nuñez (2015).

When MFC and electrodialysis work simultaneously, the system is called Microbial Desalination Cell. MFC generates electricity while treating wastewater since specific microorganisms are able to convert the chemical energy of organic matter into electricity. Then, electricity production drives a conventional desalination process based on electrodialysis. Thus, salts are partially separated from an initial saline solution (feed), which could be either, brackish water or seawater. Part of feed is mixed with the saline ions separated by the electrodialysis membranes, thus generating the concentrate solution, rejected from the MDC with no later use. The part of the feed with lower salt concentration becomes the product of the electrodialysis process. This would be the feed of a subsequent desalination process. However, MDC might be able to generate fresh water if the salt concentration of the initial solution is low enough.

The combination of MFC and electrodialysis desalination process might represent a great solution, decreasing the cost of desalination and treating wastewater at the same time [Cao et al., 2009]. The microbes used in the start-up protocol were Geobacter sulfurreducens, which after some chemical procedures became electroactive cells.

Even before the function has started, some preparation must be done as:

- an electrodialysis stage under abiotic conditions, to test the viability of the device for desalination
- introducing mixtures in the system, like:
  - recirculation of 70% v/v ethanol/water, in order to sterilize the cell
  - a gasification of N_2/CO_2 (80:20) through the MDC for two hours to guarantee ethanol evaporation and an anoxic environment inside the device. This last action optimizes later the bacteria's colonization on the anode surface.

Cells are structured in three parts: a central desalination compartment, a cathodic chamber and an anodic chamber. Moreover, the desalination compartment is separated from the others by an Anion Exchange Membrane (AEM) and a Cation Exchange Membrane (CEM). MDC, when fully developed might consist in a set of alternative compartments, each one limited by an AEM and a CEM.

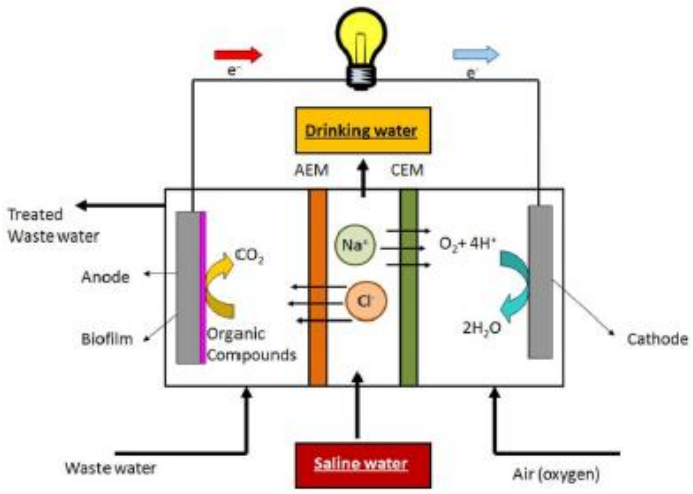


Figure 3 Diagram of MDC Units (Ortiz et al., 2015)

The interesting feature about this technology is that no energy input is needed, since the microorganisms introduced in the anodic chamber, produce the energy required. These bacteria produce electrons through the oxidation of organic matter to CO_2, once the bacteria colonize the anode (biofilm). Furthermore, the cathodic chamber is fed with a catholyte, then the electrons start traveling to the cathode, where the reduction begins. Due to both reactions, a potential difference is established between the electrodes with the migration of electrons. The concentration of sodium bicarbonate located in the saline compartment starts to decrease thanks to the potential difference. While the loss of electrons decreases the negative potential of the anode attracting the anions of chlorine, the opposite situation in the cathode attracts the cathodes of sodium.

After the biofilm pre-growth, the desalination compartment is introduced, what requires the disassembly of the whole system. This entire step could require around 20 days in a lab scale

to be completed (Meng et al., 2014), being the usual volume 300 ml or less, and the biggest scale known to be used 1 litre (Jacobson et al., 2011; Zuo et al., 2014).

Apart from being a good solution for the drawbacks commented before, the configuration of the cells could bring limitations. What is more, some functional problems have been discovered such as the increase of the internal resistance and the change in the behaviour of biofilm growth and bacteria performance. Such as changes in the behaviour, were proved to be a consequence of the pH variations in the anodic chamber. Still, tests suggested that cathode pH was not as critical as the anode pH since the last one has a strong impact on the anodic biofilm growth.

4.1 Volume of the Chambers

This parameter is one of the most decisive in the configuration of the cells, being determinant for its efficiency. As the experience shows (Table 1), compartments volumes for anolyte and catholyte could determinate the energy cost to perform desalination. Then, because of the low ratio of volumes in the study presented after this section [Ortiz at al, 2015], its efficiency is even more remarkable. What is more, compared with the percentage of desalination obtained in other start-up protocols, none reached more than 50% of the efficiency.

Table 1 Desalination performance in MDC studies (Ortiz et al., 2015)

	Start-up Protocol	Salt	Removal (%)	COD[1] (%)	Ref.
100:33:1	Transfer of pre-adapted MFC anode	5 g L^{-1} NaCl	88	-	(Cao et al., 2009)
36:11:1	Transfer of pre-adapted MFC anode	20 g L^{-1} NaCl	80	-	(Chen et al., 2011)
4:4:1	1 week anode in-situ stabilization	0.5 g L^{-1} NaCl	95.8	-	(Zuo et al., 2014)
4:2:1	Inoculation with a mixture sludge	35 g L^{-1} NaCl	42	74-77	(Zhang et al., 2015)
3:3:1	Transfer of pre-adapted MFC anode	5 g L^{-1} NaCl	46	25	(Meng et al., 2014)
1.5:1.8:1	Transfer of pre-adapted MFC anode	20 g L^{-1} NaCl	<84	72-94	(Kim and Logan 2013)
1:2:1	Inoculate of a pre-adapted biofilm	5 g L^{-1} NaCl	43	-	(Mehanna et al., 2010a)
1:2:1	40 days anode in-situ stabilization	20 g L^{-1} NaCl	37	-	(Mehanna et al., 2010b)
1:1:1	Bicarbonate desalination	5 g L^{-1} NaCl	87	53	In this study
1:1:1		2.5 g L^{-1} $NaHCO_3$	94	49	In this study

[1]: COD. Percentage of Chemical Oxygen Demand removal

4.2 Operational Conditions

The reactor used by the MDC described by Ortiz et al (2015) was manufactured by ElectroCELL, company focus on very specific constructive and operational conditions. Thus, the device was built along the lines of a plate heat exchanger, in where graphite plates would act as electrical collectors and polypropylene compartments would be sealed by neoprene gaskets. Basically, the exchanger creates a dynamic design interactive with the chambers, all of which contain 70 cm^3 of its respective inputs, injected through flow rates of 75 mL min^{-1}. Also, in this specific study of MDC, the effective area projected for the electrode was set to 100 cm^2. The system would be fed by three tanks of 2 L volume for anolyte, catholyte and saline solution, with different products depending on the chamber:

- the anode chamber fresh water is supplemented with 25mM of acetate
- the cathode chamber is fed with a catholyte (3.55 g L^{-1} Na_2SO_4, in this case)
- the central compartment receives a 5 g L^{-1} $NaHCO_3$ (Sodium Bicarbonate) or a NaClO concentration depending on which stage the function is on (Start-up or desalination).

However, the substances could change depending on the technology used by the device. At the same time, bicarbonate ions are still the general way to solve the anode pH and conductivity variations, reaching the best removal efficiency at lab scale.

The acetate acts as the fuel for the biofilm through it oxidation to CO_2 ($C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + e^- + 8H^+$) creating electricity, while in the cathode the fluid is responsible of the reduction of water ($2H_2O + 2e^- \rightarrow H_2 + 2OH^-$).

The experimental set-up would operate under a static room temperature of 30 degrees, as well as, anaerobic conditions thanks to the constant flushing of a mixture composed by N_2/CO_2 (80:20) into the tanks.

4.3 Switch on Protocol

Basically, the protocol could be separated in three steps, starting with a testing process, continuing with the start-up procedure and ending with the desalination function of the cell.

4.3.1 Testing

Initially, it begins with the application of electric potential (3 V) to check the performance of the cell and its viability for the desalination process, applying the potential under abiotic conditions. The potential obeys the following equation:

$$E_{cell} = E_{cathode} + E_{anode} + R_{cell} \cdot I_{cell}$$

$$E: potential\ (mV)\ ;\ \ R: resistance\ (\Omega);\ \ I: electric\ current\ (mA)$$

The experience with conventional technologies similar to MDC, like electrodialysis, has proved that the electric current starts to drop from the beginning of the function [Ortiz et al., 2005]. While the potential is applied, electric current starts to decrease due to the drop of the conductivity that the water in the desalination chamber suffers (Fig. 4a). Indeed, after 24 hours and a desalination of 68.6% shows a decrease of 75% in the electric current (Fig. 4b).

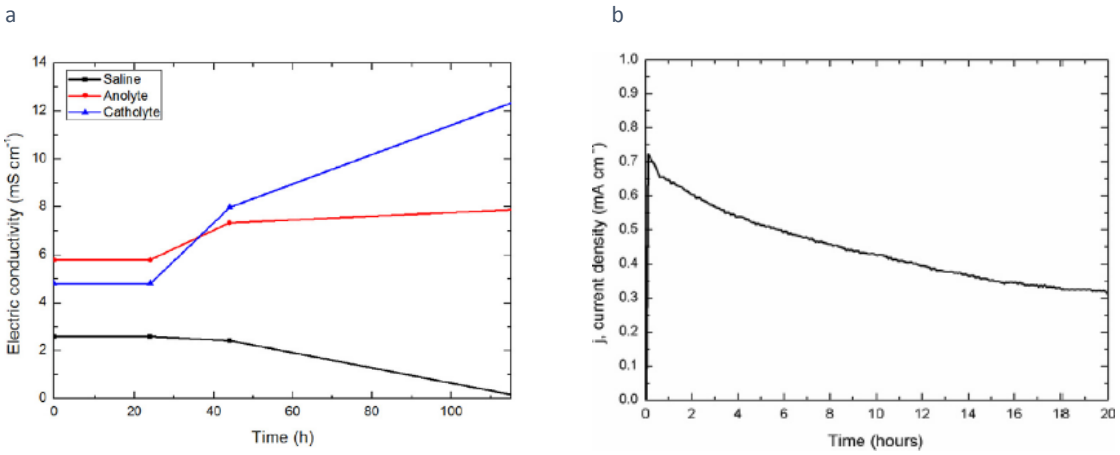


Figure 4 (a) Electric conductivity in the three chambers; (b) Electric current during the desalination process (Ortiz et al., 2015)

4.3.2 Start-up Procedure

Following the steps, the microbial anode is sterilized because of the ethanol/water solution. For two days, the mixture is gassed, after what the anode functions in a period of 20 hours, executed through a non-interventional process (batch-mode).

Thus, this inoculation leads to some changes in the behaviour of the system to maintain the cell potential constant. Not only did the anode potential drop followed by the cathode potential, but the current density increased due to the organic matter, which provides electric current due to the oxidation process.

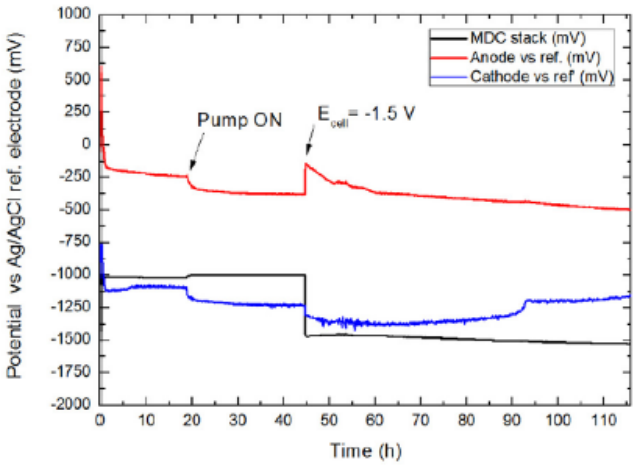


Figure 5 Potential in chambers and MDC unit (Ortiz et al., 2015)

As it is represented in figure 5, the behaviour of the system may change from the theory, as it happens with the electric current through the desalination progress. As an example, it has been observed a decrease of 33% in the current after 20 hours of operation, because of the lack of mixing in the solution.

In the following 24 hours, a stable current output is reached. Then, the voltage is extended to increase the discharge and the electric current of the biofilm, raising the current 330%. While it is on its way of reaching the highest point, the electric conductivity of the saline compartment would decrease till accomplish a desalination of 94% of the initial bicarbonate ion.

Therefore, these last events affect the electric current generation making it decrease, concluding with the statement that desalination itself caused this situation.

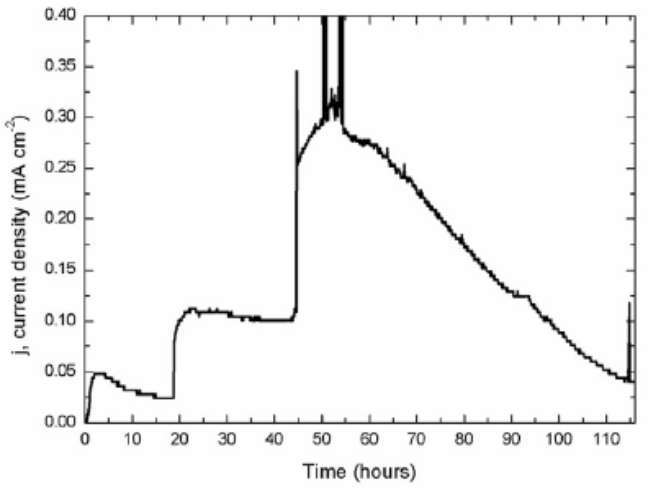


Figure 6 Electric current behaviour during the process previous to the desalination (Ortiz et al., 2015)

Additionally, the start-up progression is considered to be finished about 100 hours since the switch on protocol has begun. This moment approximately marks the point when the colonization of biofilm could provide a suitable energy support for the system.

4.3.3 Desalination

Reached this point a replacement and refilling stage starts, including:

- the replacement of the substance in cathode chamber with 2 L of NaClO 3 g L^{-1}
- a refreshment of the anolyte
- the saline solution was changed to a 0.2 L solution of NaCl 5 g L^{-1}, which is done to assure electron donor availability during the whole desalination

Because of the previous steps, now the system operates without any energy support, e.g., the fixed potential used until now. All the procedures done, had as a goal to reach this point. While the oxidation reaction persists at the time, it is obvious seeing a change on the reduction because of the new concentration of NaClO ($ClO^- + H_2O + 2e^- \rightarrow Cl^- + 2OH^-$).

Lastly, through the run of this last stage, the system could remove 65% of the NaCl particles content in the saline compartment during the first 18 hours [Meng et al., 2014]. Therefore, accomplishing a higher rate than other studies within 18 days of function. Prolonging this situation during 65 more hours, the conductivity would drop 10 times compared to the previous supported stage. Meanwhile, the anolyte and catholyte conductivity would remain stable.

Concluding the desalination after 196 hours, the removal rate stood at 87% comparable to others technologies used daily in the industry. Hence, this efficiency is a result of the biofilm performance, affected by the slight increase in the pH of the anode on this step.

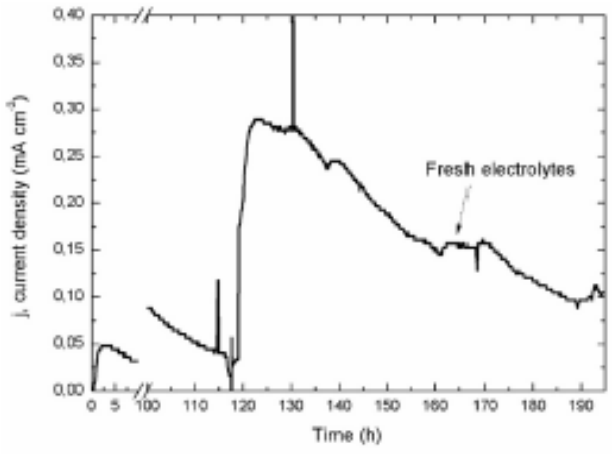


Figure 7 Electric current behaviour during the desalination process (Ortiz et al., 2015)

Specifically, this experiment moved forward as a discontinuous system. Therefore, after a determinate period the function would stop, so the substances working in the MDC could be refreshed and the outputs extracted.

After the experimentation, MDCs have proved its feasibility to perform an efficient desalination within an optimized period, due to the lack of pre-running the system as an MFC. Neither was required a disassembly for incorporating the anode into the MDC, simplifying the protocol.

4.4 Conclusion

In the study, Microbial Desalination Cells is presented as a suitable possibility to act as a pre-treatment for the desalination of saline water into fresh water, achieving 87% desalination in just 3 days. As a pre-treatment, it is thought to be an excellent support for well-established technologies such as reverse osmosis desalination or electrodialysis.

The start-up protocol, allows the device to operate without power supply along with an environmentally-friendly process. This condition of the technology resides in two main situations: the possibility of using MDC's outputs in other procedures and the use of specific volumes for the chambers, which would decrease the production of detrimental substances. Thus, making the prototype a real option to contribute solving the energetic and environmental problems present in the current desalination stations.

5. Electrodialysis

As a response to the many times this concept has appeared through the document, a brief explanation of the function and applications follows ahead. This text is based in a colloquium imparted in the University of Sevilla [Ortiz J. M., 2017].

It processes consists in the use of chemical batteries. Hence, making of the different polarities in the anode and cathode of which the battery is made, a to separate the dissolved ions in the fluid being desalinated. Moreover, helped by pairs of anodic and cathodic membranes alternated, the atoms travel to the chambers where the poles are located.

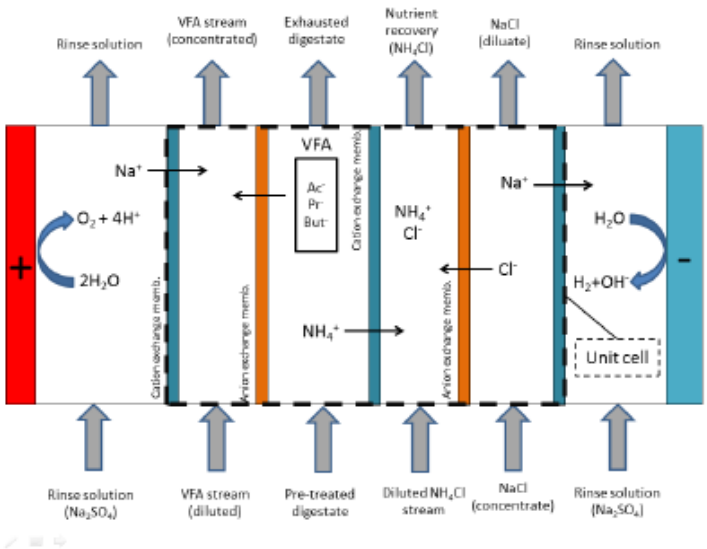


Figure 8 Electrodialysis Cell Unit for wastewater (Metaelectrodialysis) (Ortiz J. M., 2017)

Far from being on experimental phase, this technology has been used already in real situations, as is the case of the plant filtering the river Llobregat, Spain. This plant performance is driven by reverse electrodialysis equipment (EDR) technology. Thus, the production of desalinated water in the area has increased by 1 m^3 s^{-1}, partially solving some drought issues and guaranteeing around 10% of the reservoir's capacity.

Apart from not being an established worldwide application yet, ED viability is proved. This energy has the lowest energy cost, just after the auxiliary use of MDC in the RO systems, comparing their cost with the rest methods being studied for desalination in Figure 9.

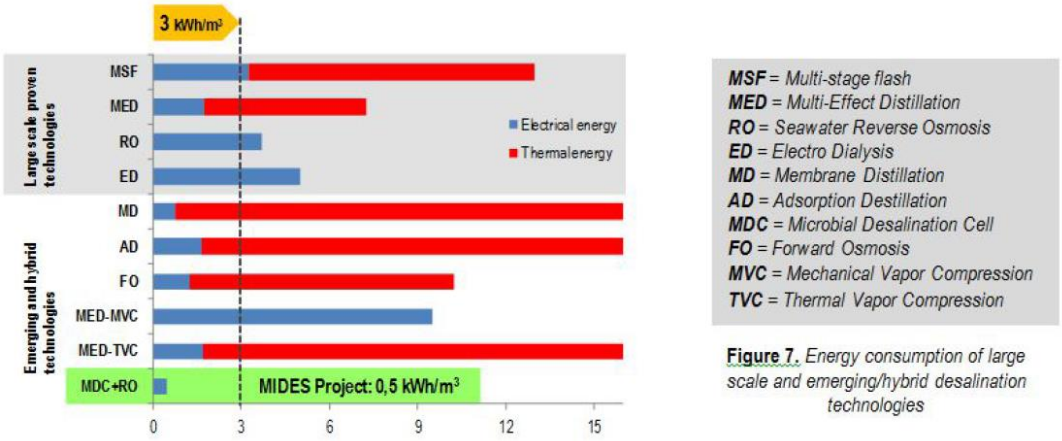
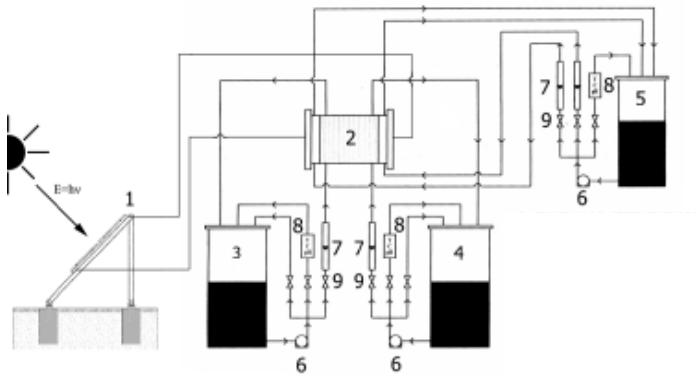


Figure 7. *Energy consumption of large scale and emerging/hybrid desalination technologies*

Figure 9 Comparison between the cost of new and traditional desalination treatments

On the contrary, the opposite concept (to use the salinity gradient to generate energy) was born as one of the new generation of renewable energies, focused on the production of suitable water from treated wastewater and saline water – either, brackish water or seawater -. This made the European Horizon 2020 program interested in this field, leading to the REvivED water research. This research made possible the cooperation between countries, in order to make this technology the new standard for desalination of seawater.

Investment has brought some investigation to this discipline, focus on decrease the energy cost or even to make it zero. On this search, some experiments like the co-application with other renewable energies, like solar energy, are giving great results at lab scale.



1. Photovoltaic generator
2. Electrodialysis reactor
3. Diluted tank
4. Concentrated tank
5. Anolyte/catholyte tank
6. Pumps
7. Flowmeter
8. Thermometer, Conductivity meter and pH-meter
9. Valve

Figure 10 Co-application of a Photovoltaic panel in an ED system

6. Thermoeconomic Analysis and Evaluation

As a thermoeconomic analysis, a brief explanation of the fundaments comprehended by this science starts the chapter. This first part is expected to make easier for the reader the understanding of the whole section.

6.1 Thermoeconomic[1]

As it is defined in many works:

"*Thermoeconomics is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations, but crucial to the design and operation of a cost-effective system. We can consider thermoeconomics are based on the exergy concept, the term exergoeconomics can also be used to describe the combination of exergy analysis and economics*." (Bejan et al., 1996, page 405)

In particular, some techniques have been developed for evaluating the thermodynamic inefficiencies of systems: exergy destructions and exergy losses. Knowledge of these costs is very useful for improving the cost-effectiveness of the system.

Additionally, this analysis could have different goals, like:

- to calculate separately the costs of each product generated by a system having more than one product
- to understand the cost formation process and the flow of costs in the system
- to optimize specific variables in a single component
- to optimize the overall system

The main purpose of thermoeconomics from all commented above is to determine the temporal cost of outputs in the installation. Because of its temporal condition, methods like

[1] This section is primarily based on Bejan, Adrian; Moran, Michael & Tsatsaronis, George (1996) Thermal Design & Optimization. New York: John Wiley and Sons page 405-462

the levelization approach should be used, in order to take into consideration the variations from year to year.

When we talk about exergoeconomics, two main types of flows are defined, the inputs and the outputs. In this case, the input (fuel, F) is used to generate the product and the output (products or losses, P or L) is what results from the system. Moreover, the difference between these last two types of output is their utility, being these products the goal of our process and the losses what it is wasted in our way to obtain the goal.

However, besides the flows commented, there is another type distinguished from the rest. This flow is linked with the letter "W" and refers to the power generated or absorb in the system.

As an analysis focused on these flow's exergetic temporal cost, those are defined with the symbol $\dot{C}$, followed by a letter depending of the type of flow studied. Furthermore, the exergetic temporal cost, could be represented as the product between the exergetic unit cost and its exergetic power:

$$\dot{C}_k = c_{e,k} \cdot \dot{E}_{e,k} \quad [€ \cdot h^{-1}]$$

In this case, the exergetic power of the power flow is mentioned with the symbol $\dot{W}$.

Frequently when focused on installations costs, a balance of the overall system is formulated:

$$\dot{C}_{P,TOTAL} + \dot{C}_{W,TOTAL} = \dot{C}_{F,TOTAL} + \dot{Z}$$

On this balance, the variable $\dot{Z}$ correspond with the expenditure made in capital investment and operating and maintenance ($\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM}$) through the life of the system. Furthermore, this cost is calculated as the expenses made, throughout the lifecycle.

6.2 Thermoeconomic Analysis of Microbial Desalination Cells

Created by the tool: Visio® by Microsoft Office, figure 11 represents the different flows generally observed in this type of cells, which have been numbered to facilitate the study and posterior understanding of the system.

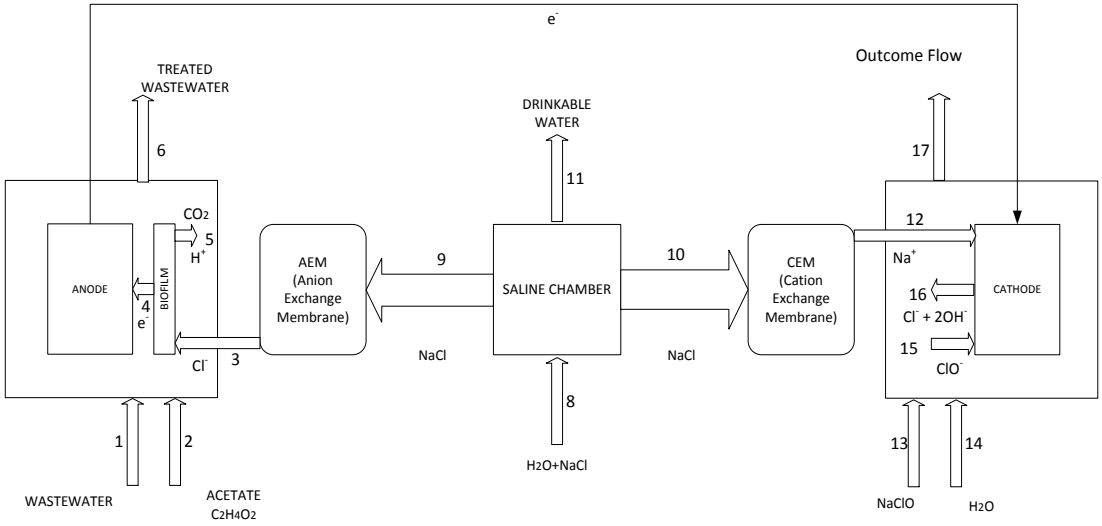


Figure 11 Flows representation of a Microbial Desalination Cell considering negligible heat losses.

The total heat equals zero in the balance formulated of the over-all system. Accordingly, this claim comes from the disregarding of the possible losses as heat in the system, considering them too low for their consideration.

Before presenting the flows, some other simplifications are made. The Figure 11 is physically separated into three zones coinciding with the chambers built in the system. The membranes, which indeed separate each zone, are considered as components interacting with the zones in contact with them, although they are not part of any of these zones.

Each chamber has its own substance to work with, as explained during the experimentation process with the MDC, even though the volume of each flow might be the same or not. Thus, it depends primordially on the relation between the volumes of the chambers. The optimization of this ratio is investigated in this section, as well as the optimization of many other characteristics of the system.

Firstly, before explaining the procedures followed to calculate the costs, a wider explanation of the flows and reactions, about which the MDC technology consists, are made zone by zone.

6.2.1 Saline Chamber

The first zone, located in the centre of the cell might be conceived as a primordial part. Indeed, this chamber is the one which contains the principal fuel and product flow in the entire installation, the water to be desalinated and the desalinated water, respectively.

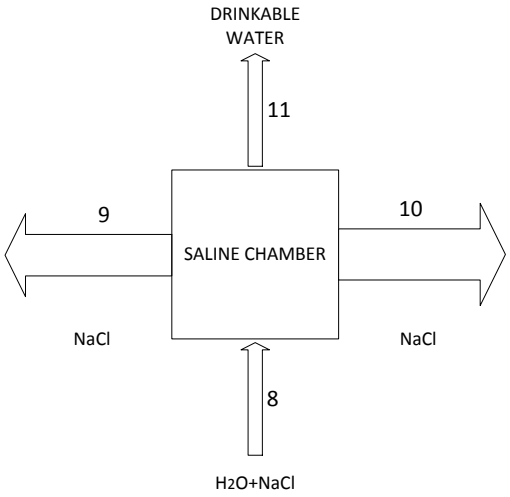


Figure 12 Zone 1

In the saline chamber, the water needed to be desalted is the input. Procedure only possible thanks to the interaction between membranes and this chamber. These membranes make use of the potential difference established between the electrodes built into the other zones, to make their function possible.

Once the procedure of desalination is finished, clear and mostly desalted water is left, making of it the principal output of this chamber.

Keeping this in mind, the equations representing the flows of this zone are:

$$Fuel = \dot{E}_8$$

$$Product = \dot{E}_{11}$$

$$Losses = 0$$

$$\dot{E}_{11} = \dot{E}_8 - \dot{E}_9 - \dot{E}_{10}$$

$$\dot{C}_{11} = \dot{C}_8 + \dot{Z}_1 \qquad \text{(Zone's Balance)}$$

The fuel as expected, is the only input on the first zone, in fact, the main input of the system. The product is considered to be the difference between exergy powers of clean water produced from the desalination and the one coming from the flows interacting with the membranes.

Losses equal zero, constant statement through the development of this study in this zone. Maintaining this statement constant in the system depends on the utility given to the outputs.

6.2.2 Anodic Chamber

The second zone corresponds to the anodic chamber, formed by the case, the anode and its respective flows. This zone includes two procedures without which the desalination could not be accomplished, the growth of the biofilm and the creation of the current supporting the power needs in the installation.

Initially, the procedure previous to desalination (Start-up) allows the creation of a structure (biofilm) made by the electroactive organisms, which existence is essential for this technology. These organisms come from the wastewater, treated while the structure is built. Hence, once the growth of the biofilm in the anode is enough, it interacts with the inputs and the anode through the oxidation to create electric current.

While the electric current is considered a product, the treated wastewater is a secondary product, depending if it is used later in other process or not. The CO_2 and the hydrogen cations expelled by the biofilm during the reaction are not stemmed under consideration as a singular flow because those fluids exit the chamber with the treated wastewater, and it has already been considered into this flow.

The inputs injected in this chamber are the wastewater itself, acetate and chlorine anions coming from the interaction of the saline water with the anodic membrane. Although the accumulation of chlorine helps to raise the potential difference, it is considered part of the treated wastewater flow as it is the CO_2. Thus, all these substances exit the chamber simultaneously once the desalination is stopped. Moreover, the acetate input makes possible the oxidation in the biofilm, when it interacts with the H_20 molecules, being stemmed as a singular flow.

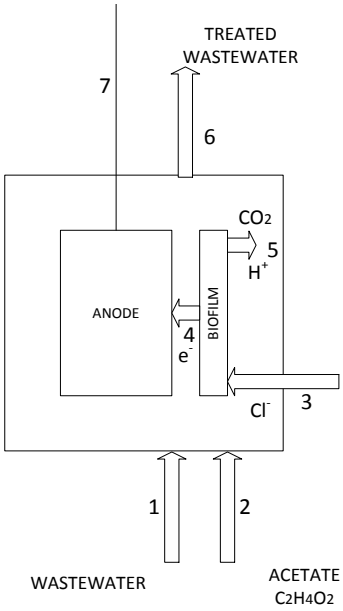


Figure 13 Zone 2

Figure 13 illustrates the flows and it is used as a lead to evaluate the equations for the products, losses and fuels of this zone.

$$Fuel = \dot{E}_2 + \dot{E}_1 + \dot{E}_3$$

$$Product = \dot{E}_7 + \dot{E}_6$$

$$Losses = 0$$

In this case, the fuel comes from the acetate, the wastewater and the chlorine anions, which makes possible the function of this chamber. Meanwhile, the products are the electric current (electrons movement towards the cathode chamber) and the treated wastewater, where the products of the oxidation have been taken under consideration. Then:

$$\dot{E}_6 = \dot{E}_1 - \dot{E}_4 + \dot{E}_5 + \dot{E}_3$$

$$\dot{C}_6 + \dot{C}_7 = \dot{C}_2 + \dot{Z}_2 \qquad \text{(Zone's Balance)}$$

In this case, it has been estimated that the treated wastewater is either recirculated or used in another treatment to completely purify it, making the losses equal zero again.

6.2.3 Cathodic Chamber

The last zone is the cathode chamber, which is now formed by the cathode, the chamber and its respective flows. This zone is responsible for receiving the current produced in the anodic chamber, which is used to power the reduction reaction.

This reduction makes use of the electrons and the water introduced into the chamber, to power it and to drive the desalination of the water. This reaction together with the one in the second zone, increment the potential of the side chambers, making possible the decrease of salinity in the central component and rising it in the others. This potential works attracting the anodes and cathodes to the side chambers thanks to the movement of the electrons.

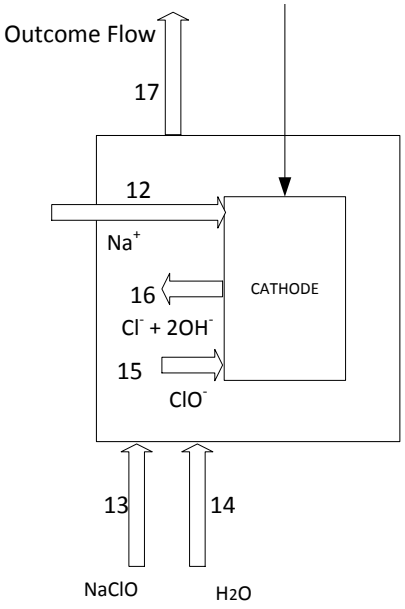


Figure 14 Zone 3

The equations defining the third zone are:

$$Fuel = \dot{E}_{13} + \dot{E}_{14} + \dot{E}_{12} + \dot{E}_{7}$$

$$Product = \dot{E}_{17}$$

$$Losses = 0$$

$$\dot{E}_{17} = \dot{E}_{12} + \dot{E}_{16} + \dot{E}_{14}$$

$$\dot{C}_{17} = \dot{C}_{13} + \dot{C}_{7} + \dot{Z}_{3} \qquad \text{(Zone's Balance)}$$

As specified before, this is the location where the electrons are received, thus this flow is considered as a fuel, as well as the rest of inputs. Accordingly, the cations resulting from the interaction of saline water with the cation exchange membrane, the water and a solution of NaClO are also the fuels for this chamber.

Lastly, the effluent of the chamber is stemmed as a product. Due to substances included in the output as the Na^+, these form others like Na(OH), which could be used later through the RO process.

6.3 Hypothesis

Once the exergetic analysis is finished, it is necessary to determinate some equations that help with the resolution of the formulated problem. These equations used like hypothesis are taken from the texts available in the subject Análisis Termodinámico de Procesos Industriales Chapter 6 by C. Gomez Camacho.

- The increment of each exergetic unit cost from fuel flows equal zero

$$\Delta_i^e \, c^F = 0 \rightarrow \frac{\dot{C}_e^F - \dot{C}_i^F}{(\dot{E}_e^F - \dot{E}_i^F)} = c_i^F \; (\forall F \in e)$$

- The increment of each exergetic unit cost from product flows are the same

$$\Delta_i^e\, c^P = \frac{\dot{C}_e^P - \dot{C}_i^P}{(\dot{E}_e^P - \dot{E}_i^P)} \equiv c^P\ (cte., \forall P \in e)$$

- The losses have the same treatment their origin had, meaning those flows act as fuels or products.
- If there is only one product, the exergetic unit cost of it is calculated in the exergetic balance.

6.4 Equations

Once, the hypothesis has been presented and the study of each zone is finished, the equations resulting from the study of the entire system are:

$$\begin{cases} \dot{E}^F = \dot{E}_8 + \dot{E}_2 + \dot{E}_1 + \dot{E}_{13} + \dot{E}_{14} \\ \dot{C}^F = c_8 \cdot \dot{E}_8 + \left(c_2 \cdot \dot{E}_2 + c_1 \cdot \dot{E}_1\right) + \left(c_{13} \cdot \dot{E}_{13} + c_{14} \cdot \dot{E}_{14}\right) \end{cases}$$

$$\begin{cases} \dot{E}^P = \dot{E}_{11} + \dot{E}_6 + \dot{E}_{17} \\ \dot{C}^P = c_{11} \cdot \dot{E}_{11} + c_6 \cdot \dot{E}_6 + c_{17} \cdot \dot{E}_{17} \end{cases}$$

$$\begin{cases} \dot{E}^L = 0 \\ \dot{C}^L = 0 \end{cases}$$

Having the balance formulated for the overall system, these equations can be expressed like:

$$\begin{cases} c_{11} \cdot \dot{E}_{11} + c_6 \cdot \dot{E}_6 + c_{17} \cdot \dot{E}_{17} = \\ c_8 \cdot \dot{E}_8 + \left(c_2 \cdot \dot{E}_2 + c_1 \cdot \dot{E}_1\right) + \left(c_{13} \cdot \dot{E}_{13} + c_{14} \cdot \dot{E}_{14}\right) + \dot{Z}_{tot} \end{cases}$$

The function of the system couldn't be possible without the existence of the geobacter in the wastewater, which chemical potential is transformed into work, specifically electrical work. Accordingly, the work appears as electric current in the anode, thanks to the transmission of electrons from the biofilm to the anode, traveling lastly to the cathode to finish the chemical battery process. This transformation may be explained through a function expressed by Gibbs' free energy, the chemical potential and the electrical work.

$$dG(n_c) = \sum_c (\mu_B\,(n_c) \cdot dn_B) + \ dW_{electr}^{anode \leftrightarrows cathode} \qquad \mu_B \doteq \left(\frac{\partial G(T,p,n_B)}{\partial n_B}\right)_{T,p,n_B}$$

The function of Gibbs has been adapted to the circumstances, keeping the temperature and the pressure constant and leaving the amount of substance as the only variable.

The information about how the chemical potential may be transformed and the equations used have been taken from *Gómez Camacho. C, Termodinámica: Segundo Curso de Grados de Ingeniería. Sevilla: Universidad de Sevilla (2013-2014)* in the sections 11 & 15.

6.5 Economical Overview of Components and Procedures

In this section, the cost related to the purchase of what is needed in order to build and make function the cell is studied by groups, which are thought to represent the total cost initially. In Table 2, these groups representing the total cost are summarized.

Table 2 Components to study through the economic analysis

Membranes
Cases
Electrical Current
Tanks
Fluids

6.5.1 Costs Disregarded

In our system, some costs are considered so low, that the election of their respective components or materials is left to the free will of the next designer. Despite the importance of a correct configuration for the system, if the main concepts are followed, it is possible to conceive this technology in infinite ways.

The disregarded costs are:

- Membranes design and construction
- Cases design and construction
- Tanks design and construction
- Electrical consumption in the start-up process
- Saline water input in the central chamber
- Outputs of the chambers

The different costs related to the elections of material or volume flow, do not interfere much in the final cost of the cells. Apart from the relevance given to the flows in the previous study, the cost of the outputs is not considered in the economic evaluation. This is because the use or destinations for these flows are out of the study that has been made, then any affirmation about this flows are just an assumption.

6.5.2 Pumping

As expressed before, the volume of saline water intake and the outputs do not cause by itself perceptible changes in the total cost, although the energy consumed to move the fluids may vary the cost. This cost mainly due to pumping saline water, either coming from the sea, from deposits or to equipment, where pre-treatments are made. In contrast with the costs of the volume of fluid, the costs produced by the pumps have a relevant impact on the total cost of the installation.

In order to give an approximate value for the cost due to pumping, the use of generally accepted ratios to calculate the cost of the feed pumped are made as a hypothesis:

$$0.75\left[\frac{kWh}{m^3\ product}\right]\cdot 0.45\left[\frac{m^3\ product}{m^3\ feed}\right]\cdot 0.0625\left[\frac{€}{kWh}\right]=0.0211\left[\frac{€}{m^3\ feed}\right]$$

The volume intake used for the sum is 10 $\left[\frac{m^3}{h}\right]$:

$$10\left[\frac{m^3\ feed}{hour}\right]\cdot 24\left[\frac{hour}{day}\right]\cdot 365\left[\frac{days}{year}\right]=87600\left[\frac{m^3\ feed}{year}\right]$$

Finally resulting in:

$$0.0211\left[\frac{€}{m^3\ feed}\right]\cdot\ 87600\ \left[\frac{m^3\ feed}{year}\right]=1848.36\left[\frac{€}{year}\right]$$

This is the energy cost for every year of work of the technology, due to the pumping of water.

6.5.3 Chemicals

Table 3 represents the cost related to the chemical needed in order to proceed with the function of the cells during a full year of operation.

Table 3 Chemicals used during the function

Chemicals	Composition	Amount [1]	Cost per Amount [2]
Acetate	0.025 M (1.64 g L^{-1})	15	19.38 € per 6 L
Na2SO4	3.55 g L^{-1}	30	16.15 € per 3 Kg
NaHCO3	5 g L^{-1}	23	23.83 € per 6 Kg
NaClO	3 g L^{-1}	23	18.96 € per 4 L
N2/CO2	80:20	1	60€ per 4.2 m^3
Ethanol/Water	70 % v/v	1	23 € per L
TOTAL			**1843 € per year**

[1]: Amount of recipients

[2]: Amount of substance in the recipient bought

7. MIDES Project coordinated by FFC Aqualia

MIDES project has born as a response to the worldwide rising population, which threaten the future sustainability of our planet. By using MDC as an energy-saving procedure interacting with desalination, this type of projects is expected to help decreasing major issues like environmental stability. The project is based on research activities of the Institute IMDEA Water [Borjas, 2016].

Co-financed by the EU Horizon 2020 program and coordinated by FFC Aqualia, MIDES project the search for new technologies focused on how to reduce the energy consumption of a conventional desalination process. Therefore, this project aims to make of traditional procedures, as reverse osmosis, less damaging to the environment.

What led to the idea of implementing MDC in the MIDES system, was the energy-cost owned by reverse osmosis installations (10 times higher than the conventional energies). The Microbial Desalination Cells are designed to remove ions from saline water in a process powered by electroactive bacteria. Also, the liberation of electrons from these bacteria allows the use of these electrons to power the cell itself, making of this implementation an efficient option for desalination.

This revolutionary procedure is aiming to reduce by one-fifth the current consumption of desalination energies (2.5 $kWh\,m^{-3}$). Even though, the target required by the European Commission about half of the saving. Moreover, it has shown attractive characteristics as an energy efficiency between 92 and 98 % or a capacity of 0.5 m^3 per m^2 of cell surface used in the system. (Ortiz J. M., 2017)

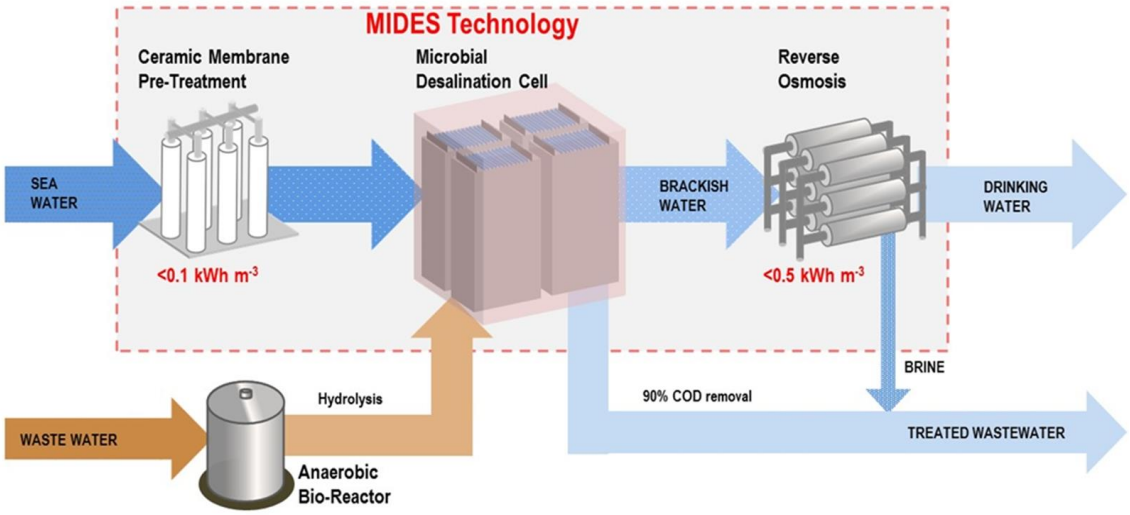


Figure 15 Future implantation of MDC technology in Reverse Osmosis Installations

As it is illustrated in figure 15, the MIDES system is thought as a complementary component for the RO installations. Thus, working pre-treating the seawater, which reduces the energy consumption of RO while reaching the same usual percentage of desalination.

The MIDES system consists of a ceramic membrane starting the process of desalination, followed by the MDC. Located after, the RO equipment complete the clearance of the seawater, making it safe for the human consumption.

The installation is built with an Anaerobic Bio-Reactor and an exit for waste products. The first component would provide bacteria to the cells thanks to hydrolysis and the second allows the waste to leave the system, so it does not interfere with the filtration.

8. Preliminary Assessment

8.1 Economic Input for the Use of MDC Technology in RO Plants

This section consists in the use of real samples of saline water as an intake in the MDC in order to evaluate the function of a system composed of the cell and followed by a RO plant. The procedure makes use of the program ROSA by The DOW Chemical Company to study the energetic cost of the desalination procedure. Moreover, the variables evaluated to study the process are the salinity and recovery percentage needed, so the power consumption of the RO plant stays constant around a value of 0.5 $kWh \cdot m^{-3}$.

As Figure 16 represents, there are power consumptions in this application due to auxiliary equipment, which is going to be disregarded in our assessment. The disregarding of these costs comes from the usual application of the auxiliary equipment in the systems composed by MDCs, being generally the same for each one and so its costs. Also, the power consumption of the cell equals zero because the energy needed is produced by itself, as it has been explained through this document.

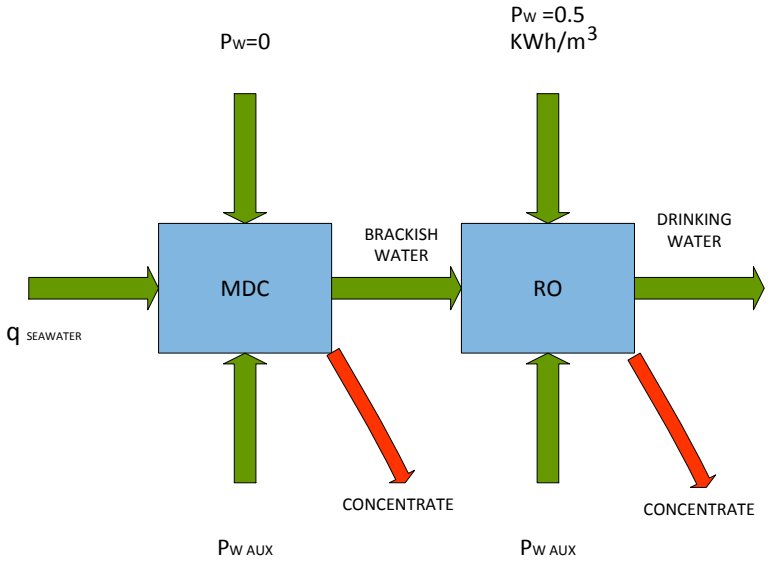


Figure 16 Basic function of MDC applied to RO plants

The evaluation of the installation is made using saline water with the composition of the Red Sea, because of its high salinity and temperature compared to the salinity of reference (0.035 $kg \cdot kg^{-1}$). Thus, this example could help defining the worst-case scenario for our installation, because of the influence that these variables have for changing the efficiency of the procedure.

Table 4 Composition in ppm of the sample of saline water coming from Saudi Arabia (Temp=26ºC)

pH	**Ca^+**	**Mg^+**	**Na^+**	**K^-**	**$CO3^-$**	**HCO_3**	**$SO42^-$**	**Cl-**	**F^-**	**$NO3^-$**	**B^+**	**SiO_2**	**TDS**
7.8	500	1540	13300	490	2.3	126.8	3240	23180	0	0	5.3	0	**42389**

Some other specifications of the system can be determined by the program, like how many elements compose the serial of membranes and the prototype of those membranes. The number of elements is generally between 7 or 8 and because of the level of salinity, the number of elements chosen is 8, so the biggest amount of permeable is desalted. The membrane chosen was SW30ULE-440i because its specifications adapt better to our intake flow conditions.

The evaluation of the function consists of the study of different conditions of the seawater, through its dilution by taking different amounts of solute in each experiment. In addition, the dilution of this water is made by a pre-treatment previous to the MDC, which is not estimated in this evaluation.

The equations and nomenclature used through the assessment are:

$$B \equiv Solute \;\; ; \;\; A \equiv solvent \;\; ; \;\; SW \equiv Seawater \;\; ; \;\; \Delta m_B \equiv Solute\ taken\ from\ seawater$$

$$C_{SW} = \frac{m_B}{V_A}\left[\frac{mg}{L}\right] \quad ; \quad \frac{C_{SW}}{C_{DIL}} \quad ; \quad \Delta m_B = \frac{m_B}{k}$$

$$C_{concentrate} = \frac{m_B + \Delta m_B}{V_A} = \frac{m_B + \frac{m_B}{k}}{V_A} = \frac{\frac{m_B}{V_A} \cdot (1 + k^{-1})}{\frac{V_A}{V_A}} = \left(1 + \frac{1}{k}\right) \cdot C_{SW} = \frac{(k+1)}{k} \cdot C_{SW}$$

$$C_{DIL} = \frac{m_B - \Delta m_B}{V_A} = \frac{m_B - \frac{m_B}{k}}{V_A} = \frac{\frac{m_B}{V_A} \cdot (1 - k^{-1})}{\frac{V_A}{V_A}} = \left(1 - \frac{1}{k}\right) \cdot C_{SW} = \frac{(k-1)}{k} \cdot C_{SW}$$

This last equation could be transformed into:

$$\frac{C_{SW}}{C_{DIL}} = \frac{k}{k-1}$$

Finally, the experiments result in four different dilutions of seawater, which are used to find the value of the constant k:

- 1st dilution of half of the solute $\left(\frac{C_{SW}}{C_{DIL}} = 2 = \frac{k}{k-1}\right) \rightarrow k = 2 \rightarrow \Delta m_B = \frac{m_B}{2}$
- 2nd dilution of two-thirds of the solute $\left(\frac{C_{SW}}{C_{DIL}} = 3 = \frac{k}{k-1}\right) \rightarrow k = \frac{3}{2} \rightarrow \Delta m_B = \frac{2 \cdot m_B}{3}$
- 3rd dilution of three-fourths of the solute $\left(\frac{C_{SW}}{C_{DIL}} = 4 = \frac{k}{k-1}\right) \rightarrow k = \frac{4}{3} \rightarrow \Delta m_B = \frac{3 \cdot m_B}{4}$
- 4th dilution of three-fifths of the solute $\left(\frac{C_{SW}}{C_{DIL}} = \frac{8}{3} = \frac{k}{k-1}\right) \rightarrow k = \frac{5}{3} \rightarrow \Delta m_B = \frac{3 \cdot m_B}{5}$

Initially, the original sample of seawater (10 $m^3 \cdot h^{-1}$ & $Recovery = 50\%$) was used to obtain the results of energy consumption, so later a comparison of the energy save could be made with the four experiments and the same feed flow. The first dilution was disregarded because the salinity of the water was considered still too high, making impossible to reach an acceptable consumption of power. After applying a generally accepted recovery percentage of 80 % in the rest of the cases, this value was changed in order to experiment with different possible solutions. After some experimentation, the values of the recovery percentage showed an increase in the energetic efficiency of the system, when decreased between 50 and 65, maintaining the efficiency of the desalination. Finally, from all the cases studied, the best results were reached with the second and fourth dilution and a recovery percentage of 55% and 62.5%, respectively.

All the data obtained is represented in the Annex at the end of this document.

The results for the consumption of power of the systems are $P_{W\ HPP\ DIL\ 2} = 9.46\ kW$ & $P_{W\ HPP\ DIL\ 4} = 11.87\ kW$, which allow maintaining a value around 0.5 kWh · m^{-3} for the consumption of power of the RO equipment.

Also, the power saved by the cell is calculated as a 97% of the power produced while expanding the brine flow out of the RO plant, and not the 100% because of the different losses through this process:

$$P_{W\ SAVE} = 0.97 \cdot P_{W\ BRINE\ FLOW} = 0.97 \cdot\ q_V \cdot\ \Delta p$$

$$P_{W\ SAVE\ DIL\ 2} = 0.97 \cdot 4.45 \left[\frac{m^3}{\text{h}}\right] \cdot \frac{1}{3600}\left[\frac{h}{s}\right] \cdot 25.50\ [bar] \cdot 100\left[\frac{kPa}{bar}\right] = 3.0575[kW]$$

$$P_{W\ SAVE\ DIL\ 4} = 0.97 * \frac{3.75}{3600} * 32.61 * 100 = 3.295\ [kW]$$

$$\left(Being: \quad 1bar = 10^5 Pa = 10^5 \frac{kg}{m \cdot s^2} \qquad \& \qquad 1W = \frac{kg \cdot m^2}{s^3}\right)$$

Then:

$$Specific\ Energy\ Consumption\ (SEC) = \frac{P_{W\ HPP} - P_{W\ SAVE}}{q_P} \frac{[kW]}{\left[\frac{m^3}{h}\right]}$$

$$SEC_{DIL\ 2} = \frac{9.46 - 3.0575}{5.55} = 1.154 \left[\frac{kWh}{m^3}\right]$$

$$SEC_{DIL\ 4} = \frac{11.87 - 3.295}{6.25} = 1.372 \left[\frac{kWh}{m^3}\right]$$

Finally, paying attention to the result obtained for the original sample and making the same calculations than previously, the energy saved thanks to the dilutions is:

$$P_{W\ HPP\ ORI} = 23.19\ [kW] \quad ; \quad P_{W\ SAVE\ ORI} = 8.76[kW] \quad ; \quad SEC_{ORI} = 2.88 \left[\frac{kWh}{m^3}\right]$$

$$E_{SAVED} = SEC_{ORIG} - SEC_{DIL}$$

$$E_{SAVED\ DIL\ 2} = 1.732 \left[\frac{kWh}{m^3}\right] \qquad \& \qquad E_{SAVED\ DIL\ 4} = 1.514 \left[\frac{kWh}{m^3}\right]$$

$$\downarrow Energetic\ Costs_{DIL} = E_{SAVED\ DIL} \cdot \left[\frac{m^3\ prod}{m^3\ feed}\right] \cdot \left[\frac{€}{kWh}\right] \cdot \left[\frac{m^3\ feed}{year}\right] = \left[\frac{€}{year}\right]$$

$$\downarrow Energetic\ Costs_{DIL\ 2} = E_{SAVED\ DIL\ 2} \cdot 0.55 \cdot 0.0625 \cdot 87600 = 5215.485 \left[\frac{€}{year}\right]$$

$$\downarrow Energetic\ Costs_{DIL\ 4} = E_{SAVED\ DIL\ 4} \cdot 0.625 \cdot 0.0625 \cdot 87600 = 5180.72 \left[\frac{€}{year}\right]$$

The estimation of fresh water cost is out of the aim of this work, since it is difficult to estimate capital costs of a developing technology. Therefore, the cost analysis is focused on the cost saving attributable to the decrease of the specific energy consumption as a results of the seawater dilution.

8.2 Implantation of MDC in small-capacity desalination systems driven by renewable energies

Once the general economic calculation is made for the use of MDC's technology in RO plants, another case is considered in order to improve the cost of energy consumed. This suggestion is driven by the recent tendency of implanting energies which impact on the environment is null or reduced. Those consist in the installation of the MDC cells in RO plants powered by technologies like solar photovoltaic (PV) and wind-powered energies.

These considerations could possible reduce to zero the energy needs created from not environmental-friendly procedures, like the combustion of fuels. In addition, the volume of feed flow used for this section is the same than the one used in the general economic operations, maintaining coherence in the calculations.

Also, the development of this section takes as a hypothesis that the RO plant is a consumption of the photovoltaic and the wind-powered systems.

8.2.1 Wind Powered Technology

The characteristic owned by wind energy makes it a feasible way to power desalination processes. The data to proceed with the economic evaluation was obtained from Peñate, Castellano, Bello & García-Rodríguez (2011).

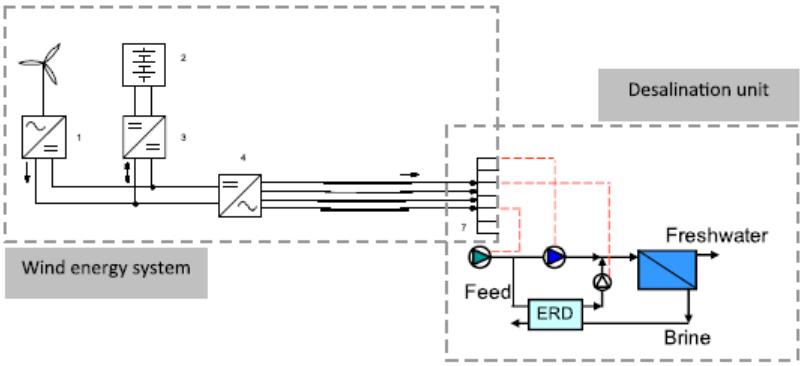


Figure 17 Scheme of a wind energy system connected to a seawater RO desalination plant

The specific case studied is the use of off-grid wind energy systems, which are the ones driving the desalination system. The wind energy system will be powered by a wind generator (FUHRLANDER FL100), which consumption of power is 100 kW. In addition, three wind turbines of this type are coupled to a RO plant with a feed capacity of 1000 $m^3 \cdot d^{-1}$, which has been proven to produce 159000 m^3 annually of suitable water.

Based on this research, it has been estimated that $P_{W\ Wind\ Turb} \approx P_{W\ RO}$ then:

$$\frac{kW_{Wind}}{m^3/h} = 1\left[\frac{kW_{Wind}}{kW_{RO}}\right] \cdot SEC = SEC$$

This data should be used in case of evaluating the capital cost of a desalination project.

It has been demonstrated that the energetic consumption is the same than the RO plant with the MDC cell implanted, consuming energy from the grid. However, this energy is produced by the turbines, so the whole consumption will be a cost saved in the annual balance:

$$\downarrow Energetic\ Costs_{WIND} = E \cdot \left[\frac{m^3\ prod}{m^3\ feed}\right] \cdot \left[\frac{€}{kWh}\right] \cdot \left[\frac{m^3\ feed}{year}\right] = \left[\frac{€}{year}\right]$$

Using the hypothesis that the cost of the energy stayed still since 2012 (70 € per MWh) in Europe (Data from the International Energy Agency).

$$\downarrow Energetic\ Costs_{WIND\ 0} = 2.88 \cdot 0.5 \cdot 0.07 \cdot 87600 = 8830.1\left[\frac{€}{year}\right]$$

$$\downarrow Energetic\ Costs_{WIND\ 2} = 1.154 \cdot 0.55 \cdot 0.07 \cdot 87600 = 3892\left[\frac{€}{year}\right]$$

$$\downarrow Energetic\ Costs_{WIND\ 4} = 1.372 \cdot 0.625 \cdot 0.07 \cdot 87600 = 5286.2\left[\frac{€}{year}\right]$$

Finally:

$$Total\ savings_{DIL\,2} = 5215.485 + 3892 = 9107.485\ \left[\frac{€}{year}\right]$$

$$Total\ savings_{DIL\,4} = 5180.72 + 5286.2 = 10466.92\ \left[\frac{€}{year}\right]$$

8.2.2 Solar energy

Meanwhile, the other suggestion is exemplified with a photovoltaic installation driving the RO plant. Keeping the procedure used for the wind-powered energy the energetic cost saved from the desalination of seawater with solar equipment obeys the following equation:

$$\downarrow Energetic\ Costs_{SOLAR} = E \cdot \left[\frac{m^3\ prod}{m^3\ feed}\right] \cdot \left[\frac{€}{kWh}\right] \cdot \left[\frac{m^3\ feed}{year}\right]$$

Using the hypothesis that the cost per kWh is 10c€ (Lillo,I. 2017).

$$\downarrow Energetic\ Costs_{SOLAR\,0} = 2.88 \cdot 0.5 \cdot 0.1 \cdot 87600 = 12614.4\left[\frac{€}{year}\right]$$

$$\downarrow Energetic\ Costs_{SOLAR\,2} = 1.154 \cdot 0.55 \cdot 0.1 \cdot 87600 = 5559.972\left[\frac{€}{year}\right]$$

$$\downarrow Energetic\ Costs_{SOLAR\,4} = 1.372 \cdot 0.625 \cdot 0.1 \cdot 87600 = 7511.7\left[\frac{€}{year}\right]$$

Finally:

$$Total\ savings_{DIL\,2} = 5215.485 + 5559.972 = 10775.46\ \left[\frac{€}{year}\right]$$

$$Total\ savings_{DIL\,4} = 5180.72 + 7511.7 = 12692.42\ \left[\frac{€}{year}\right]$$

9. Conclusion

Main conclusions of the assessment performed are as follows:

- The literature survey carried out shows than the use of Microbial Desalination Cell (MDC) in water desalination is a developing technology with interesting future prospects.
- Equations of a general assessment from a thermoeconomic point of view have been developed in this work.
- A preliminary thermoeconomic analysis has been solved with scarce data available. This problem is attributable to the recent development of MDC´s and to the originality of the analysis performed.
- Based on the literature, a feasible value of seawater dilution by a MDC is selected as one-half of the initial seawater salinity – see Table 1 -. Besides that, other output salinities analysed were selected as one-third, one-fourth and two-fifths of the initial seawater salinity.
- Under the assumption that seawater of Saudi Arabia is diluted by one-half by MDC´s prior a conventional reverse osmosis process, the following conclusions can be highlighted:

- Concerning solar PV-driven desalination, energy consumption decrease may result in cost saving greater than 0.22 €·m^{-3}.
- Application of wind power may reduce their operating cost attributable to energy up to 0.19 €·m^{-3}.

These results are relevant since the cost of fresh water production with conventional energy sources is around 0.5 €·m^{-3}. However, if renewable energy-driven desalination with conventional energy backup is considered, the fresh water cost would be around 1.3 €·m^{-3}.

- Affordable fresh water cost for renewable energy-driven desalination could be possible in the near future by using MDC technology. Therefore, the development of MDC´s seems to be important to develop small-size desalination systems.

10. Improvements & considerations for future projects related to this topic

Some suggestions about related future work:

- Progress in the detail of the thermoeconomic analysis.
- Look for research made about the efficiency of new configurations of the MDC.
- Proceed with a deeper assessment of the implementation of MDC in reverse osmosis plants driven by renewable energies.
- Obtain experimental data about other dilutions of seawater through the implementation of MDC in reverse osmosis plants.

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Glossary

Annex

Reverse Osmosis System Analysis for FILMTEC™ Membranes

Case 0 Original Sample

System Details

Feed Flow to Stage 1	10.00	m³/h
Raw Water Flow to System	10.00	m³/h
Feed Pressure	66.78	bar
Flow Factor	0.85	
Chem. Dose (100% H2SO4)	0.00	
Total Active Area	327.01	M²

Pass 1 Permeate Flow	5.00	m³/h
Pass 1 Recovery	50.00	%
Feed Temperature	26.0	C
Feed TDS	42563.76	mg/l
Number of Elements	8	
Average Pass 1 Flux	15.29	lmh

Osmotic Pressure		
Feed	30.42	bar
Concentrate	63.59	bar
Average	47.00	bar
Average NDP	19.11	bar
Power	23.19	kW
Specific Energy	4.64	kWh/m³

Stage	Element	Nº of Passes	Nº of Elements	Feed Flow (m³/h)	Feed Press (bar)	Recirc Flow (m³/h)	Conc Flow (m³/h)	Conc Press (bar)	Perm Flow (m³/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	SW30ULE-440i	1	8	10.00	66.44	0.00	5.00	65.01	5.00	15.29	0.00	0.00	496.29

Water Classification: Seawater with DOW Ultrafiltration, SDI < 2.5

Stage Details

Stage 1	Element	Recovery	Perm Flow	Perm TDS	Feed Flow	Feed TDS	Feed Press
	1	0.15	1.52	160.88	10.00	42563.76	66.44
	2	0.14	1.15	238.03	8.48	50190.78	66.15
	3	0.11	0.82	361.75	7.33	58034.89	65.92
	4	0.09	0.57	558.67	6.50	65336.16	65.72
	5	0.06	0.38	865.73	5.94	71507.68	65.56
	6	0.05	0.25	1320.17	5.56	76331.03	65.41
	7	0.03	0.18	1941.05	5.30	79935.39	65.27
	8	0.02	0.13	2706.72	5.13	82606.62	65.14

Pass Streams (mg/l as Ion)					
Name	Feed	Adjusted Feed	Concentrate	Permeate	
			Stage 1	Stage 1	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00
K	483.79	483.79	960.20	7.41	7.41
Na	13131.33	13131.33	26087.36	176.16	176.16
Mg	1520.47	1520.47	3036.39	4.65	4.65
Ca	493.66	493.66	985.86	1.49	1.49
Sr	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO3	12.22	12.22	26.73	0.00	0.00
HCO3	128.45	128.45	250.07	2.28	2.28
NO3	0.00	0.00	0.00	0.00	0.00
Cl	23481.61	23481.64	46674.53	290.28	290.28
F	0.00	0.00	0.00	0.00	0.00
SO4	3282.16	3282.16	6560.47	4.06	4.06
SiO2	0.00	0.00	0.00	0.00	0.00
Boron	5.26	5.26	8.77	1.74	1.74
CO2	0.98	0.98	2.30	1.25	1.25
TDS	42563.72	42563.76	84631.73	496.29	496.29
pH	7.80	7.80	7.92	6.37	6.37

Scaling Calculations			
	Raw Water	Adjusted Feed	Concentrate
pH	7.80	7.80	7.92
Langelier Saturation Index	0.92	0.92	1.63
Stiff & Davis Stability Index	-0.13	-0.13	0.38
Ionic	0.88	0.88	1.83
TDS (mg/l)	42563.72	42563.76	84631.73
HCO3	128.45	128.45	250.07
CO2	0.98	0.98	2.30
CO3	12.22	12.22	26.73
CaSO4 (% Sat)	24.68	7.95	62.49
BaSO4 (% Sat)	0.00	0.00	0.00
SrSO4 (% Sat)	0.00	0.00	0.00
CaF2 (% Sat)	0.00	0.00	0.00
SiO2 (% Sat)	0.00	0.00	0.00
Mg(OH)2 (% Sat)	0.21	0.08	0.71

Reverse Osmosis System Analysis for FILMTEC™ Membranes

Case 2 Dilution of two-thirds of the solute

System Details

Feed Flow to Stage 1	10.00	m³/h
Raw Water Flow to System	10.00	m³/h
Feed Pressure	27.23	bar
Flow Factor	0.85	
Chem. Dose (100% H2SO4)	0.00	
Total Active Area	327.01	M²

Pass 1 Permeate Flow	5.55	m³/h
Pass 1 Recovery	55.50	%
Feed Temperature	26.0	C
Feed TDS	14188.46	mg/l
Number of Elements	8	
Average Pass 1 Flux	16.97	lmh

Osmotic Pressure		
Feed	10.05	bar
Concentrate	22.45	bar
Average	16.25	bar
Average NDP	10.07	bar
Power	9.46	kW
Specific Energy	1.70	kWh/m³

Stage	Element	Nº of Passes	Nº of Elements	Feed Flow (m³/h)	Feed Press (bar)	Recirc Flow (m³/h)	Conc Flow (m³/h)	Conc Press (bar)	Perm Flow (m³/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	SW30ULE-440i	1	8	10.00	26.89	0.00	4.45	25.50	5.55	16.97	0.00	0.00	154.90

Water Classification: Seawater with DOW Ultrafiltration, SDI < 2.5

Stage Details

Stage 1	Element	Recovery	Perm Flow (m³/h)	Perm TDS (mg/l)	Feed Flow (m³/h)	Feed TDS (mg/l)	Feed Press (bar)
	1	0.12	1.22	62.60	10.00	14188.46	26.89
	2	0.12	1.06	80.76	8.78	16156.93	26.60
	3	0.12	0.90	106.25	7.71	18369.88	26.36
	4	0.11	0.74	142.54	6.82	20775.16	26.16
	5	0.10	0.59	194.64	6.08	23273.52	25.99
	6	0.08	0.45	269.49	5.50	25731.15	25.85
	7	0.07	0.34	376.43	5.04	28012.03	25.72
	8	0.05	0.25	526.25	4.70	30013.24	25.61

Name	Feed	Adjusted Feed	Concentrate	Permeate	
			Stage 1	Stage 1	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00
K	161.26	161.26	359.51	2.30	2.30
Na	4377.11	4377.11	9767.77	54.84	54.84
Mg	506.82	506.82	1137.11	1.45	1.45
Ca	164.55	164.55	369.20	0.46	0.46
Sr	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO3	1.28	1.28	4.71	0.00	0.00
HCO3	42.82	42.82	92.28	0.74	0.74
NO3	0.00	0.00	0.00	0.00	0.00
Cl	7828.28	7830.55	17483.96	90.38	90.38
F	0.00	0.00	0.00	0.00	0.00
SO4	1094.05	1094.05	2456.95	1.27	1.27
SiO2	0.00	0.00	0.00	0.00	0.00
Boron	1.75	1.75	3.18	0.60	0.60
CO2	0.47	0.47	1.13	0.60	0.60
TDS	14186.19	14188.46	31689.68	154.90	154.90
pH	7.80	7.80	7.62	6.24	6.24

Scaling Calculations			
	Raw Water	Adjusted Feed	Concentrate
pH	7.80	7.80	7.62
Langelier Saturation Index	-0.01	-0.01	0.47
Stiff & Davis Stability Index	-0.64	-0.64	-0.49
Ionic Strength (Molal)	0.28	0.28	0.65
TDS (mg/l)	14186.19	14188.46	31689.68
HCO3	42.82	42.82	92.28
CO2	0.47	0.47	1.13
CO3	1.28	1.28	4.71
CaSO4 (% Sat)	6.94	7.95	17.46
BaSO4 (% Sat)	0.00	0.00	0.00
SrSO4 (% Sat)	0.00	0.00	0.00
CaF2 (% Sat)	0.00	0.00	0.00
SiO2 (% Sat)	0.00	0.00	0.00
Mg(OH)2 (% Sat)	0.07	0.08	0.07

Reverse Osmosis System Analysis for FILMTEC™ Membranes

Case 4 Dilution of three-fifths of the solute

System Details

Feed Flow to Stage 1	10.00	m³/h
Raw Water Flow to System	10.00	m³/h
Feed Pressure	34.17	bar
Flow Factor	0.85	
Chem. Dose (100% H2SO4)	0.00	
Total Active Area	327.01	M²

Pass 1 Permeate Flow	6.25	m³/h
Pass 1 Recovery	62.51	%
Feed Temperature	26.0	C
Feed TDS	15960.23	mg/l
Number of Elements	8	
Average Pass 1 Flux	19.12	lmh

Osmotic Pressure		
Feed	11.29	bar
Concentrate	30.20	bar
Average	20.74	bar
Average NDP	12.62	bar
Power	11.87	kW
Specific Energy	1.90	kWh/m³

Stage	Element	Nº of Passes	Nº of Elements	Feed Flow (m³/h)	Feed Press (bar)	Recirc Flow (m³/h)	Conc Flow (m³/h)	Conc Press (bar)	Perm Flow (m³/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	SW30ULE-440i	1	8	10.00	33.83	0.00	3.75	32.61	6.25	19.12	0.00	0.00	178.54

Water Classification: Seawater with DOW Ultrafiltration, SDI < 2.5

Stage Details

Stage 1	Element	Recovery	Perm Flow	Perm TDS	Feed Flow	Feed TDS	Feed Press
	1	0.15	1.53	60.19	10.00	15960.23	33.83
	2	0.15	1.30	81.90	8.47	18830.85	33.55
	3	0.15	1.06	115.13	7.17	22231.08	33.33
	4	0.13	0.82	166.84	6.11	26062.95	33.15
	5	0.11	0.61	248.26	5.29	30085.63	33.01
	6	0.09	0.44	370.12	4.68	33954.23	32.89
	7	0.07	0.29	579.09	4.24	37424.24	32.79
	8	0.05	0.20	871.66	3.95	40163.39	32.70

Pass Streams (mg/l as Ion)					
Name	Feed	Adjusted Feed	Concentrate	Permeate	
			Stage 1	Stage 1	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00
K	181.40	181.40	479.46	2.64	2.64
Na	4923.64	4923.68	13027.91	63.23	63.23
Mg	570.11	570.11	1517.89	1.69	1.69
Ca	185.10	185.10	492.83	0.54	0.54
Sr	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO3	1.62	1.62	7.22	0.00	0.00
HCO3	48.18	48.18	122.28	0.84	0.84
NO3	0.00	0.00	0.00	0.00	0.00
Cl	8807.91	8807.91	23320.28	104.23	104.23
F	0.00	0.00	0.00	0.00	0.00
SO4	1230.96	1230.96	3280.98	1.48	1.48
SiO2	0.00	0.00	0.00	0.00	0.00
Boron	1.97	1.97	4.12	0.68	0.68
CO2	0.51	0.51	1.49	0.72	0.72
TDS	15960.19	15960.23	42272.43	178.54	178.54
pH	7.80	7.80	7.59	6.22	6.22

Scaling Calculations			
	Raw Water	Adjusted Feed	Concentrate
pH	7.80	7.80	7.59
Langelier Saturation Index	0.09	0.09	0.69
Stiff & Davis Stability Index	-0.59	-0.59	-0.36
Ionic	0.32	0.32	0.87
TDS (mg/l)	15960.19	15960.23	42272.43
HCO3	48.18	48.18	122.28
CO2	0.51	0.51	1.49
CO3	1.62	1.62	7.22
CaSO4 (% Sat)	7.95	7.95	24.75
BaSO4 (% Sat)	0.00	0.00	0.00
SrSO4 (% Sat)	0.00	0.00	0.00
CaF2 (% Sat)	0.00	0.00	0.00
SiO2 (% Sat)	0.00	0.00	0.00
Mg(OH)2 (% Sat)	0.08	0.08	0.08